

Incorporation of bed texture into a channel evolution model

Martin W. Doyle^{a,*}, F. Douglas Shields Jr.^{b,1}

^a Department of Earth and Atmospheric Sciences, Purdue University, 1397 Civil Engineering Building,
West Lafayette, IN 47907-1397, USA

^b Research Hydraulic Engineer, USDA Agricultural Research Service–National Sedimentation Laboratory, P.O. Box 1157,
Oxford, MS 38655, USA

Received 4 January 1998; received in revised form 30 November 1999; accepted 5 January 2000

Abstract

Channel evolution models (CEM) have been developed to qualitatively describe the morphological adjustments of channels undergoing incision, but the grain size of the river bed material has not been addressed in existing evolution models. Herein, bed material grain size is incorporated into an existing CEM to describe the sequence of grain size changes. The analysis is based on the data from bed material that were available from a 1986 sampling program in northwestern Mississippi. Samples were taken along three sand-and-gravel-bed channels at 300-m intervals. To provide a comparable data set, sampling was repeated in 1996. Observed longitudinal grain size distributions were highly variable in space and time. Overall downstream fining trends were absent. Bed texture in incising channels is as dynamic as channel morphology, with composition shifting from a mixture dominated by sand to one dominated by gravel, or vice versa, within a decade or less. The modified CEM predicted direction of changes in grain size in a meandering incising channel, but not within two straightened, incising channels, most likely due to the complex influence of upstream and lateral sediment sources (bed and bank erosion). We suggest that over the temporal (10 years) and spatial scales (~ 10 to 20 km) of this study, sediment sources are the dominant factor in the development of longitudinal grain size distributions. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: bed material size; downstream fining; channel evolution models

1. Introduction

Alluvial channels are dynamic in that they adjust to changes in environmental conditions. Lane (1955)

described these changes in terms of a proportional relation:

$$QS \propto Q_s D_s \quad (1)$$

where Q = water discharge, S = channel slope, Q_s = sediment discharge, and D_s = a characteristic particle size of the river bed material. Lane's relation has been commonly used for qualitative prediction of morphologic response to disturbance in the fluvial system (Simons and Senturk, 1977; Nunnally, 1985;

* Corresponding author. Tel.: +1-765-494-0258; fax: +1-765-496-1210.

E-mail addresses: mdoyle@purdue.edu (M.W. Doyle), shields@sedlab.olemiss.edu (F.D. Shields).

¹ Tel.: +1-601-232-2919; fax: +1-601-232-2915.

Chang, 1988; Simon, 1994). When stream conditions are altered, either naturally or by human agency, in such a way as to increase water discharge (e.g. urbanization) or slope (e.g. channelization), Lane's relation predicts a proportionate increase in sediment

discharge through local entrainment or an increase of river bed material sediment size (hereafter referred to as grain size) in comparison to the previous state of the channel. Increasing sediment discharge in this way can lead to rapid changes in channel morphol-

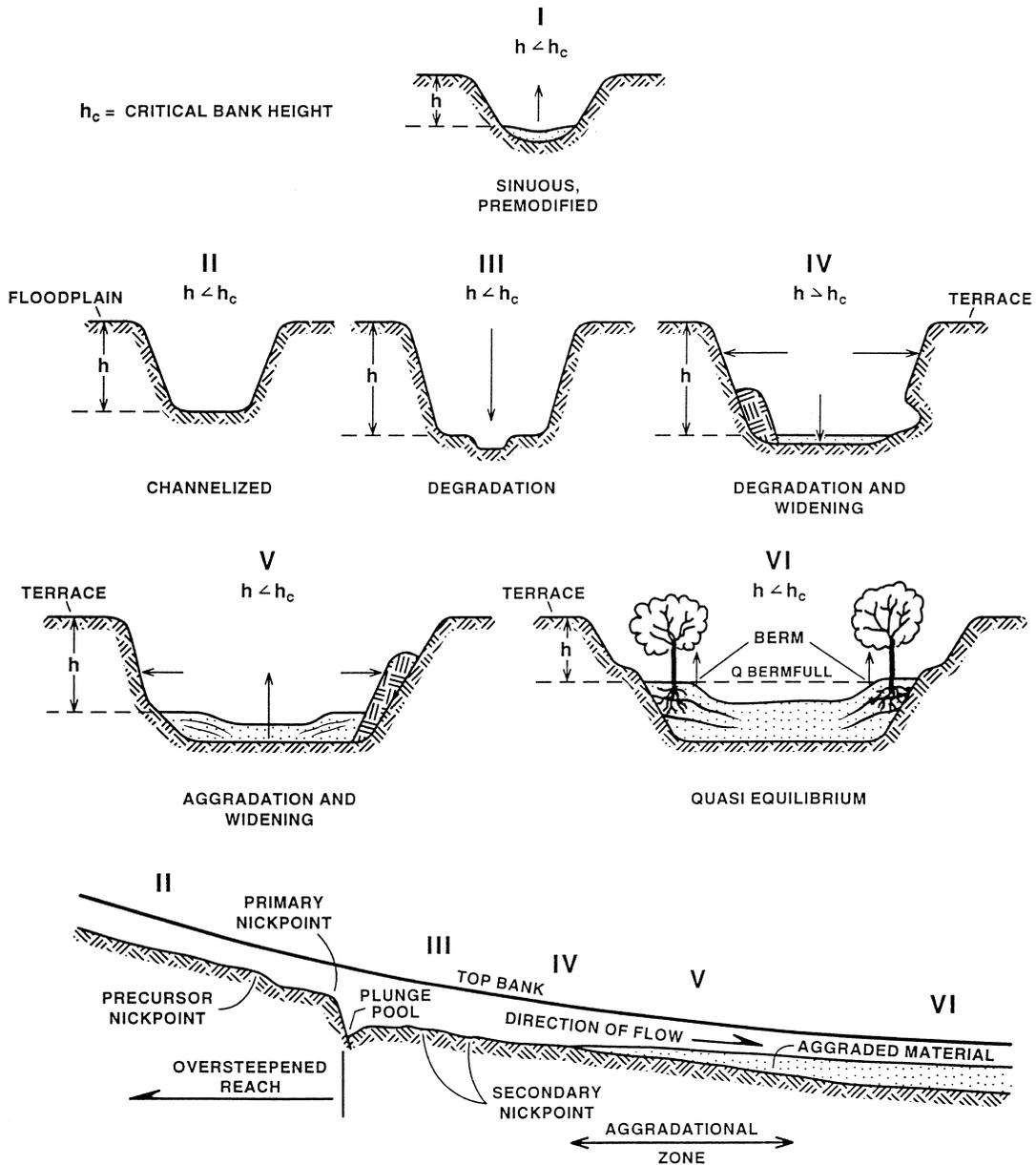


Fig. 1. Conceptual CEM. Adapted from Simon (1994) and U.S. Army Corps of Engineers (1990). Reaches are assigned in the upstream direction.

ogy including upstream degradation, downstream bed aggradation and bank instabilities along the main channel as well as adjacent tributaries (Simon, 1994).

These changes in morphology are the basis of channel evolution models (CEM). Schumm et al. (1984), among others, showed that disturbed channels follow a predictable pattern of adjustments through time which varies along the channel longitudinal profile, and can be described by a series of five process-oriented stages of development. These stages of evolution can be developed by substitutions of space for time involving the arrangement of channel cross-sections in a sequence that reflects change through time. In the case of channel incision induced by base level lowering or downstream channelization, conditions for disturbance are first reflected in the lower reaches of a channel and then migrate upstream. Schumm's model was slightly revised by Simon (1989, 1994) who developed a six-stage CEM based on data from a region similar to our study area and will be used herein for the description of evolving channels. The six stages of the Simon CEM are illustrated schematically in Fig. 1. The advantage of the CEM is its selection of relatively few key vari-

ables to represent many processes operating across a broad spatial scale. Specifically, by observing channel width, depth, bank condition (including vegetation), and thalweg profile, one may classify a channel network according to the CEM and, thus, qualitatively predict the future course of channel evolution.

Morphologic adjustments associated with channel incision have been documented by numerous field studies. For example, Galay (1983) reviews observations of channel incision including several cases of upstream-progressing bed degradation and bank widening following channelization. Harvey and Watson (1986) document degradation and widening of a channel (caused by channelization) leading to increases in channel cross-sectional area by as much as 1000%. Yearke (1971) noted incision caused by the elimination of a meander bend that lowered bed elevation 4.5 m and increased channel width up to four times. Simon (1989) correlated changes in sediment discharge (Q_s) with the six stages of the CEM for field sites in western Tennessee. Simon and Hupp (1992) classified the six stages of the CEM with regard to bed and bank adjustments as well as in-

Table 1
Changes in bed material grain size in incised and unstable channels

Reference	Study area	Channel description	Observations of grain size changes
Simon and Thorne (1996)	Washington, flank of volcano	sand/gravel-bed; unstable	As channel adjusted geometry following debris avalanche, grain size and percent gravel present increased.
Jacobson (1995)	Southeastern Missouri	sand/gravel-bed; incising	More coarse sediment and lack of fine sediment observed in locally aggrading reaches.
Simon (1989)	Western Tennessee	sand-bed; incising	Channel adjustment and recovery entailed transfer of coarse materials from upstream.
Willis (1988)	Northwestern Mississippi	sand/gravel-bed; incising	Bed fining was associated with excess upstream sediment supply and bed coarsening with low upstream sediment supply.
Simon et al. (1996)	Western Iowa	silt-bed; incising	Channel evolution and recovery was less advanced than in Mississippi or western Tennessee because of lack of sources of sand.
Kuhnle (1996)	Northwestern Mississippi	sand/gravel-bed; incising	Changes in grain size were a function of location, supply of gravel, and selective transport.
Bennett et al. (1998)	Northwestern Mississippi	sand/gravel-bed; incising	Changes in grain size occurred seasonally, with sediments becoming coarser during periods of degradation associated with higher flows and finer during low flow season when net aggradation occurred.

channel vegetation. Additional case studies of the effects of incision are available for Missouri (Emerson, 1971), Iowa (Lohnes, 1997; Daniels, 1960), Oklahoma (Barclay, 1980; Schoof et al., 1986), Mississippi (Whitten and Patrick, 1981; Kesel and Yodis, 1992), Indiana (Barnard, 1977), and the Midwest (Simon et al., 1996) in the USA, as well as Alberta, Canada (Parker and Andres, 1976), and central Italy (Rinaldi and Simon, 1998).

Existing models of incised channel evolution ignore the role of grain size in channel adjustment. Limited field observations are available in the literature, and these are encapsulated in Table 1. Changes in grain size are important because: (1) grain size represents another degree of freedom in channel response to perturbations (Hoey and Ferguson, 1997); (2) grain size has major implications for biological communities (Shields and Milhous, 1992; Wang et al., 1997); (3) grain size affects retention of pollutants within river channels (Novotny and Chesters, 1981; Langedal, 1997); and (4) equilibrium channel geometry (Bray, 1982; Hey and Thorne, 1986; Julien and Wargadalam, 1995) and sediment transport capacity are sensitive to grain size.

The intent of this study was to quantify spatial and temporal grain size changes in incising channels and place these changes within the framework of a modified CEM. The modified CEM is intended to allow qualitative predictions of grain size changes relative to existing conditions. This study also documents temporal changes in grain size, a topic that has received little attention (Bluck, 1987; Simon and Thorne, 1996). Bed material samples were collected from three incising channels in northwestern Mississippi in 1986 and 1996.

2. Modified CEM

Many processes affect temporal and spatial grain size distributions on river beds. Selective transport of finer particles and, to a lesser extent, abrasion are evidenced by downstream fining (Sternberg, 1875; Parker, 1991a,b; Kodama, 1992; Werritty, 1992; Hoey and Ferguson, 1994, 1997; Seal et al., 1997). Recent studies have shown that material recruited from channel banks can overshadow downstream

fining (Pizzuto, 1995, 1997; Rice and Church, 1996). Contributions of bank sediment can be especially important in incising channels. Indeed, Grissinger and Murphey (1986) estimated that for Goodwin Creek, an incising channel in northwestern Mississippi, sediment derived from failing stream banks accounted for about 80% of watershed sediment yield. Insight into the influence of bank material on longitudinal grain size distributions may be gained using the CEM, Lane's relation, and observations made in previous studies (Table 1). In this incorporation of grain size into the CEM, the sedimentary conditions, Q_s and D_s , are not separated and the two variables are treated as responding in tandem. Hence, response predictions are qualitative. However, where either D_s or Q_s can be constrained, prediction of morphologic response can be more certain (e.g. Darby and Thorne, 1996), whereas models allowing mutual adjustment of Q_s and D_s are currently in the development stage (Langendoen et al., in press) and therefore do not eliminate the need for qualitative conceptual models.

In Table 2, we have attempted to add bed texture to the CEM using Lane's relation. Because the CEM is applied on the reach scale, and channel incision migrates upstream, an increase in channel slope is followed by and associated with bed degradation and decrease in slope with bed aggradation. The bed texture responses indicated in Table 2 assume a supply of coarse material, in this case gravel, either fluviially or from bed and bank erosion. When sediment sources are limited to sands, bed texture changes are negligible or non-existent (Doyle, 1997) and variations within the sand-size range have little impact on channel morphology (Darby and Thorne, 1996). If the channel banks contain coarse material, then degrading Stage III and IV reaches will become coarser. Degradation implies a deficit of upstream sediment, and coarse material in the bed or banks will be recruited through bed degradation and bank collapse. While Stage V reaches also recruit material from channel banks, bed aggradation in this stage implies that the upstream supply of sediment is relatively high, and thus grain size should decrease relative to Stage IV. Finally, Stage VI aggrading beds will continue to fine (excess upstream supply of sediment) and bank erosion will decelerate. The development of inset, low berms in Stage VI will

Table 2

CEM modified to include changes in grain size. Changes in Q , S , Q_s and D_s in Lane's relation are relative to previous stage of channel evolution. Changes in Q_s as described by Simon (1989)

Stage	Stage description	Lane's relation	Status and processes
I	Premodified/ Stable	$QS \propto Q_s D_s$	Unaltered meandering channel with local erosion on outside bends, banks are densely vegetated to the flow line
II	Constructed ^a	$Q^{(+)}S^{(+)} \propto Q_s D_s$	Channel re-shaped with a trapezoidal cross-section, vegetation removed
III	Degradation	$Q^{(+)}S^{(+)} \rightarrow Q_s^{(+)}D_s^{(+)}$	Channel degradation in response to steepened gradient or increased discharge. Upstream progressing nickpoints form, bank heights increase, and bank slopes steepen because of stream downcutting
IV	Degradation and Widening	$Q^{(+)}S \rightarrow Q_s^{(+)}D_s^{(+)}$	Continued degradation and major widening as banks exceed critical height. Banks are shaped by mass wasting, leading to tilted and fallen vegetation on banks and in channel
V	Aggradation and Widening	$Q^{(-)}S^{(-)} \rightarrow Q_s^{(-)}D_s^{(-)}$	Beginning of bed aggradation and development of meandering thalweg. Continued bank widening. Woody vegetation begins to re-establish on lower bank
VI	Quasi- equilibrium	$Q^{(-)}S^{(-)} \rightarrow Q_s^{(-)}D_s^{(-)}$	Significant reduction of bank heights by channel bed aggradation and by fluvial deposition on the upper bank and slough line. Bank erosion subsides and woody vegetation extends upslope to the former floodplain.

^aThis stage is absent if adjustment is due to developments other than channel modification (e.g. urbanization or meander cut-off).

buffer the influence of the relatively small amount of material still emanating from eroding channel banks.

Selective transport of finer sediments may also influence bed texture. Coarse materials derived from bed and bank erosion may be less mobile under the imposed hydraulic stresses. Stream power (QS) levels are generally higher in Stages III and IV relative to Stage I (Simon, 1994) since slope is increased and the enlargement of the channel through erosion increases within-bank discharge. Higher levels of stream power create the opportunity for selective transport of finer materials, further promoting bed coarsening in Stages III and IV. Bed aggradation in Stages V and VI reduces reach slope and the frequency of critical shear stresses for coarser materials. However, since incising channels do not display equilibrium between sediment size and competence, selective transport may not occur. For example, Kuhnle and Willis (1992) found that the size distribution of bed load and bed material were virtually identical for a Stage IV incising channel tributary to one of our study reaches, implying equal mobility of all sediment sizes. Evidently, imposed stresses were competent to transport all material supplied to the channel. Further, frequent mobility of the coarsest grain sizes on bimodal beds increases dramatically when the fraction of sand within the bed sediment

reaches and exceeds about 20% (Wilcock, 1998). Typically, sand content in the beds of channels in our study area was well above 20%.

In addition, delivery of sediments by tributaries has been shown to disrupt downstream fining patterns (Knighton, 1980; Ichim and Radoane, 1990; Pizzuto, 1995; Rice and Church, 1996). Tributary contributions can also change dramatically in time (Rice and Church 1996), particularly as main channels evolve through stages III and IV and lower base levels for tributaries. However, existing CEMs were developed based on observations of channels receiving tributary sediment contributions from tributaries typically in phase with upstream reaches of the main channel. Thus changes in tributary contributions in response to main channel incision should be viewed as systematic effects of incised channel evolution, and not as site-specific anomalies.

3. Study area

Watersheds containing the study sites (Fig. 2) are located in the east Gulf Coastal Plain Physiographic Province bordering the eastern bluffline of the Mississippi River Valley (Fenneman, 1938). Soils, topography, and land use were typical of many streams

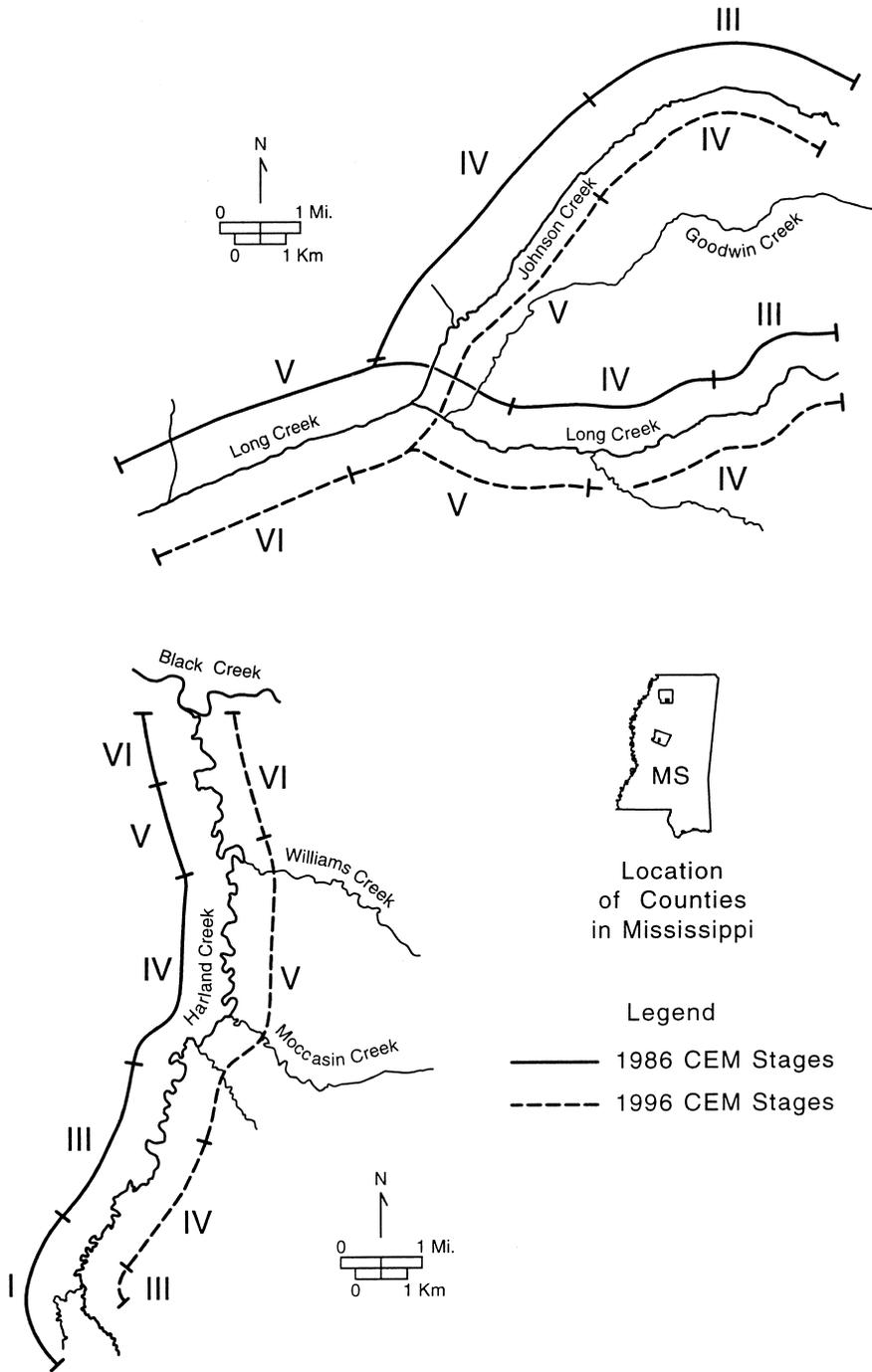


Fig. 2. Location and reach delineation of study channels.

along the eastern side of the lower Mississippi River floodplain. Ridges are capped with loess deposits, and valleys are filled with up to 3 m of alluvium derived from post-European settlement erosion overlying a complex of six or more erodible stratigraphic units which constitute three Holocene-age depositional sequences (Grissinger et al., 1982). A late Holocene meander-belt alluvium (unconsolidated sandy silt) typically overlies early Holocene massive silt. A relatively coarse-textured noncohesive channel-fill mid-Holocene unit is less abundant. The early Holocene sequence also includes gravel-bearing channel lag, bog-type, and grey-silt units that underlie the massive silt.

With little geologic control (no bedrock and infrequent erosion-resistant outcrops), channels experience unrestricted adjustment following disturbances. The area has been subjected to a series of disturbances since about 1830 (Watson et al., 1997). The disturbances (deforestation, cultivation, erosion of hillsides and valley sedimentation) were followed by periodic straightening and dredging of the channels between 1840 and 1930. When streams were straightened, they were repositioned in the valleys and, thus, present channel bed and bank materials are not necessarily former fluvial deposits and are highly variable. A series of intensive studies of three of the straightened channels (two of which contain our study sites Johnson (JC) and Long Creeks (LC) (see Fig. 2) described below) documented the response of riparian vegetation (Grissinger and Bowie, 1984), channel width-to-depth ratios (Grissinger and Murphey, 1983), and channel planform (Grissinger and

Murphey, 1984) to the highly variable streambank lithology.

Initial channelization was for the most part ineffective because channelized streams quickly filled with sediment and continued to flood. Because of this continued flooding, a second round of channelization occurred between 1930 and 1960, increasing the sediment transport capacity of the channels by as much as 50 times (U.S. Army Corps of Engineers, 1993; Shields et al., 1995). The increase in transport capacity and the lack of geologic control resulted in severe channel incision (as much as 5 m) which progressed through the main channels and into the tributaries, destabilizing the beds and banks of entire watersheds (Whitten and Patrick, 1981; Grissinger et al., 1982, Simon and Darby, 1997).

Three incised channels in northwest Mississippi were selected for field study: Harland (HC), JC, and LC (Fig. 2; Table 3). These channels were ideal for this study for several reasons. Foremost, extensive bed material sampling was performed during 1986 in all three channels, facilitating temporal comparisons. Second, all three channels were incising, as evidenced by channel widening and other characteristics mentioned earlier (Fig. 1; Table 2). Also, JC and HC had large, numerous gravel deposits present in channel beds and banks (Fig. 3), whereas gravel deposits on LC were not as frequent. Whereas all three channels are incised, JC and LC have been channelized while HC remains unstraightened, reworking its fluvial deposits. Also, grade control structures were constructed on JC in 1979 and on LC in 1986 to prevent future bed degradation that might result from

Table 3
Study site descriptions

Channel	Drainage Area (km ²)	Q_2 at mouth (m ³ s ⁻¹)	Q_s (t km ⁻² year ⁻¹)	Slope	Sinuosity	Valley slope	No. of grade control structures	Length sampled (km)
HC	161	133.1 ^a	1673 ^b	0.0011 ^a	2.1 ^a	0.0023	0	22.5
JC	54	152.9 ^c	–	0.0023 ^c	1.2 ^c	0.0028	3	12.8
LC	205	481.4 ^c	1464 ^b	0.0018 ^c	1.1 ^c	0.0020	3	16.1

^a $Q_{2.33}$.

^a Northwest Hydraulic Consultants (1987).

^b Rebich (1993).

^c Northwest Hydraulic Consultants (1989).



Fig. 3. Photographs showing (a) gravel deposits in banks along JC, and (b) mass wasting of channel banks along HC.

the upstream advancement of nickpoints (Schumm et al., 1984). Some of these structures also enhance bank stability by creating backwater conditions that induce rapid deposition for a few hundred meters upstream (Biedenharn et al., 1990). To summarize, LC and JC are heavily affected by engineering attempts to control the evolution of channel incision (straightening and grade controls), which is in con-

trast to the effects of more natural development along HC.

4. Methods

During the summer and fall of 1986, samples of bed material were collected from the three study

channels by personnel from the USDA National Sedimentation Laboratory, Oxford, MS. Individual samples (hereafter referred to as unit samples) were taken from the stream channel at 300-m intervals. The unit samples, bulk samples of the top 10 cm of the bed (weighing approximately 4 kg), were taken from the deepest point in the channel cross-section. Each unit sample was sieved at 0.5ϕ intervals (where $\phi = -\log_2 D$, D is grain size in mm) from 91 to 4.8 mm; a split of the material finer than 4.8 mm was then sieved at 0.5ϕ intervals down to 0.063 mm.

A primary objective of this study was to develop a 1996 database for comparison with the 1986 data. The need to obtain data comparable to those generated by the 1986 sampling and logistical issues acted as major constraints on sampling protocol. Every effort was made to replicate the 1986 sampling protocol in order to facilitate direct comparison of 1986 and 1996 results. Similar replication of sampling techniques was practiced by Nordin and Queene (1992) when collecting a Mississippi River bed material data set in 1989 for comparison to data collected in 1932. During the 1996 field program, initial sampling was conducted with personnel who sampled during 1986 to assure identical methods. The 1996 samples were located to coincide with those sampled in 1986 by measuring the distances along the channels using hip chains and tapes and by referring to annotated 1:24,000 maps prepared during the 1986 campaign. Field notes recorded the size of material contributed by tributaries relative to the main channel.

Each channel was divided into reaches for further study. Detailed descriptions and photographs of the channels taken in 1986 were used in conjunction with field notes to assign stages of channel evolution based on the sequence presented by Simon (1994) (Fig. 1). Each channel was divided into reaches based on the 1986 CEM stage delineations and these reaches are shown on Fig. 2. Each reach was reclassified in 1996 during collection of bed material samples. It should be noted that the number of cross sections within each reach was variable.

Minimum sample size for accurate determination of grain size percentiles has been established by Church et al. (1987) based on the size of the largest stone present. More recently, Ferguson and Paola (1997) determined minimum sample size based on

three factors: average grain size, standard deviation of the grain size distribution, and the percentile of interest. These factors are incorporated through the following equation to define a sample size, V_g , for 'good' precision (10% standard error in D_{50}):

$$\log_{10}(V_g/V_{50}) = 3.0 + 4.2\log_{10}(\sigma) + 0.9\sigma z_p \quad (2)$$

where V_g = volume of mineral sample size needed for 'good' precision, V_{50} = volume of the grain for which 50% of the material is finer, σ = standard deviation of the grain size distribution, and z_p = p th percentile point of the unit normal distribution.

A pilot study (Ferguson and Paola, 1997) was performed on JC (considered representative of the three channels) to obtain estimates of V_{50} and σ for application of Eq. (2). In a typical reach of JC, 22 unit samples were collected from a 31 m² area (Doyle, 1997). Results indicated that the minimum sample size needed for determination of D_{50} with a 10% standard error was 7.2 kg. Thus, during the 1996 field program, we used sampling protocol identical to that used in 1986; but when analyzing data from both 1986 and 1996, sieve results (mass retained on each sieve) from two adjacent unit samples were composited to meet the minimum sample size criteria. Hereafter, these composited samples are referred to as representative samples.

Data were characterized by computing D_{50} , median sizes of material coarser and finer than 2 mm (i.e., $D_{50 \text{ gravel}}$ and $D_{50 \text{ sand}}$), and percent gravel for each representative sample. Mean values of for each of these four statistics were computed for each channel and date, and differences between 1986 and 1996 were examined using t -tests. Relationships between D_{50} and the other three variables ($D_{50 \text{ gravel}}$, $D_{50 \text{ sand}}$, and percent gravel) were examined using correlation and regression. As described below, results indicated that D_{50} was the best choice for a statistic to describe the grain size distributions, and thus was used for subsequent analyses.

D_{50} values were plotted against distance upstream of the channel mouth, yielding profiles of grain size for each channel and date. Observed trends of downstream fining were tested for significance using the runs test (Blalock, 1979) as suggested by Rice and Church (1996). Reaches with abundant coarse material, and those with pronounced fining or coarsening trends were identified and the locations relative to

tributary mouths, structures, and gravel-bearing strata were noted.

Mean values of D_{50} were also calculated for 1986 and 1996 for each of the reaches delineated using the CEM classifications. Spatial changes across the reaches based on CEM classifications were evaluated in light of predictions based on the modified CEM, but no attempt was made to isolate systematic effects of channel evolution from those that were contingent upon site-specific factors.

Temporal changes in bed texture were identified, and an effort was made to discriminate between systematic and contingent effects by limiting temporal comparisons to statistics for samples representing identical points in space. For example, unit samples were collected from the same six points in reach HC1 in 1986 and 1996. Thus, the variances of D_{50} values from this reach for 1986 and 1996 were compared using an F -test, and means were compared using a t -test.

Since the 1986 and 1996 sample locations were identical, contingent effects associated with tributary locations would be the same for both dates. As noted above, we viewed changes in tributary load because of channel evolution as systematic rather than contingent effects. The recruitment of bed material from

eroding channel boundaries and upstream reaches (including tributaries) and the size of imported materials are primarily governed by morphologic processes associated with channel incision (bed degradation or aggradation and channel widening). These processes should vary systematically with time and space, and thus lend themselves to prediction and conceptual modeling. Contingent effects associated with grade control structures would be the same for 1986 and 1996 for the JC structures because they pre-dated 1986 sampling. LC structures were placed between the sample dates, and profiles of grain size were examined for the impact. No structures were constructed on HC.

5. Results

Bed material samples were composed of sand and gravel, with $D_{\max} < 45$ mm in all three channels. The channels were competent to transport all sediment sizes. Using reach-average channel slopes, typical roughness coefficients, and an assumed dimensionless shear stress of 0.047, the sizes of sediment mobilized by the 2-year discharge (which is less than bankfull) were calculated to be 50, 96, and 116 mm

Table 4

Channel	Mean D_{50} (mm)		% Change	Change significant? ^a
	1986	1996		
<i>(a) Temporal changes in mean bed material grain size of three incising channels in northwestern Mississippi</i>				
HC	5.3	3.0	–44%	Yes ($p < 0.01$)
JC	2.5	2.5	0%	No ($p = 0.98$)
LC	0.61	0.80	32%	No ($p = 0.14$)
<i>(b) Temporal changes in mean percent gravel in the bed material of three incising channels in northwestern Mississippi</i>				
HC	57	46	–20%	Yes ($p = 0.04$)
JC	46	35	–24%	No ($p = 0.10$)
LC	22	24	9%	No ($p = 0.61$)
<i>(c) Temporal changes in the mean D_{50} of the gravel fraction of the bed material of three incising channels in northwestern Mississippi</i>				
HC	11.0	10.8	–2%	No ($p = 0.83$)
JC	12.6	10.1	–20%	No ($p = 0.08$)
LC	9.9	10.4	5%	No ($p = 0.75$)
<i>(d) Temporal changes in the mean D_{50} of the sand fraction of the bed material of three incising channels in northwestern Mississippi</i>				
HC	0.47	0.48	2%	No ($p = 0.67$)
JC	0.51	0.50	–2%	No ($p = 0.62$)
LC	0.42	0.51	21%	Yes ($p < 0.01$)

^aSignificance based on two-tailed t -test.

for HC, JC and LC, respectively. Samples containing both sand and gravel were bimodal, with modes at ~11 and 0.5 mm, and the percent sand (material less than 2 mm) within samples varied from 17% to

100%, with 124 of the 129 representative samples having a sand content greater than 20%.

Bed textures were somewhat dynamic in time, especially within HC (Table 4). Changes in bed

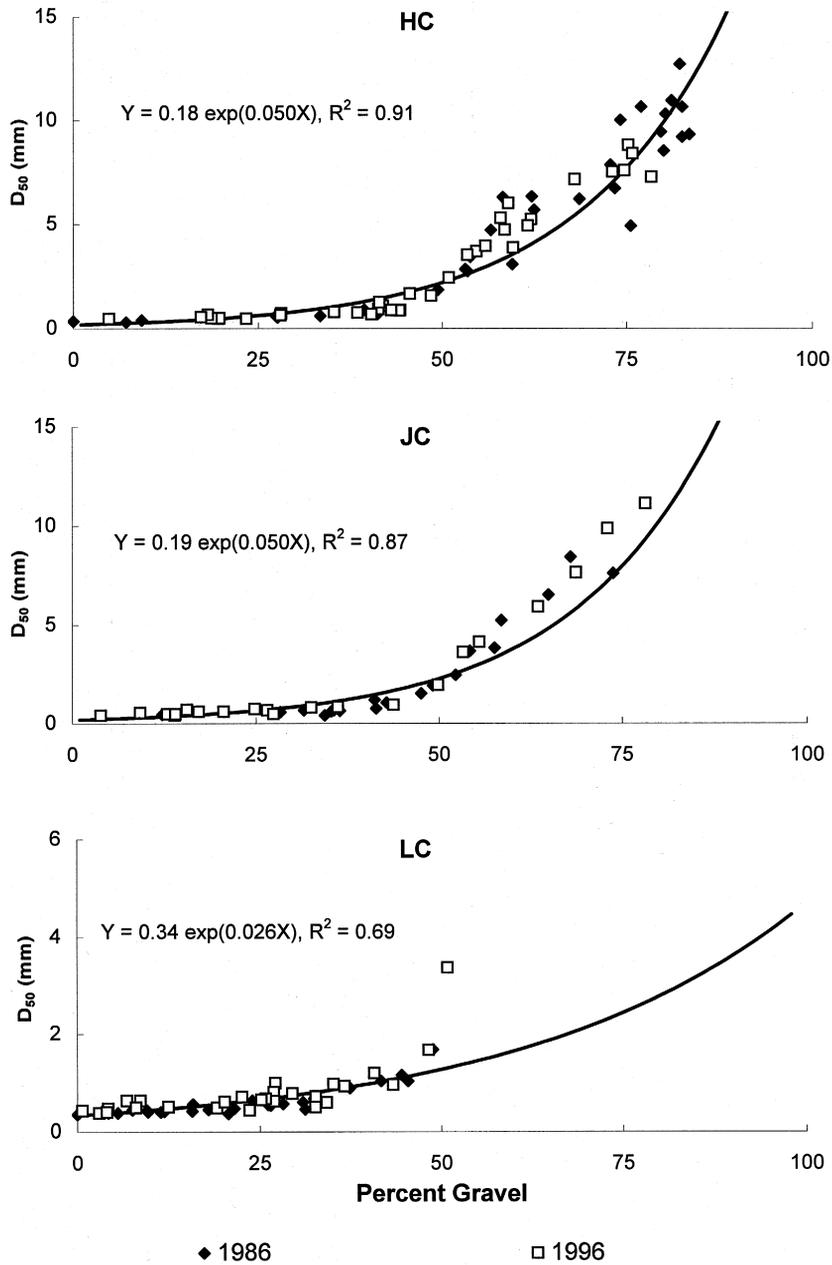


Fig. 4. Median grain size of bed material versus percent gravel in bed material for sites HC, JC, and LC. Regression lines are fit to all data (1986 and 1996).

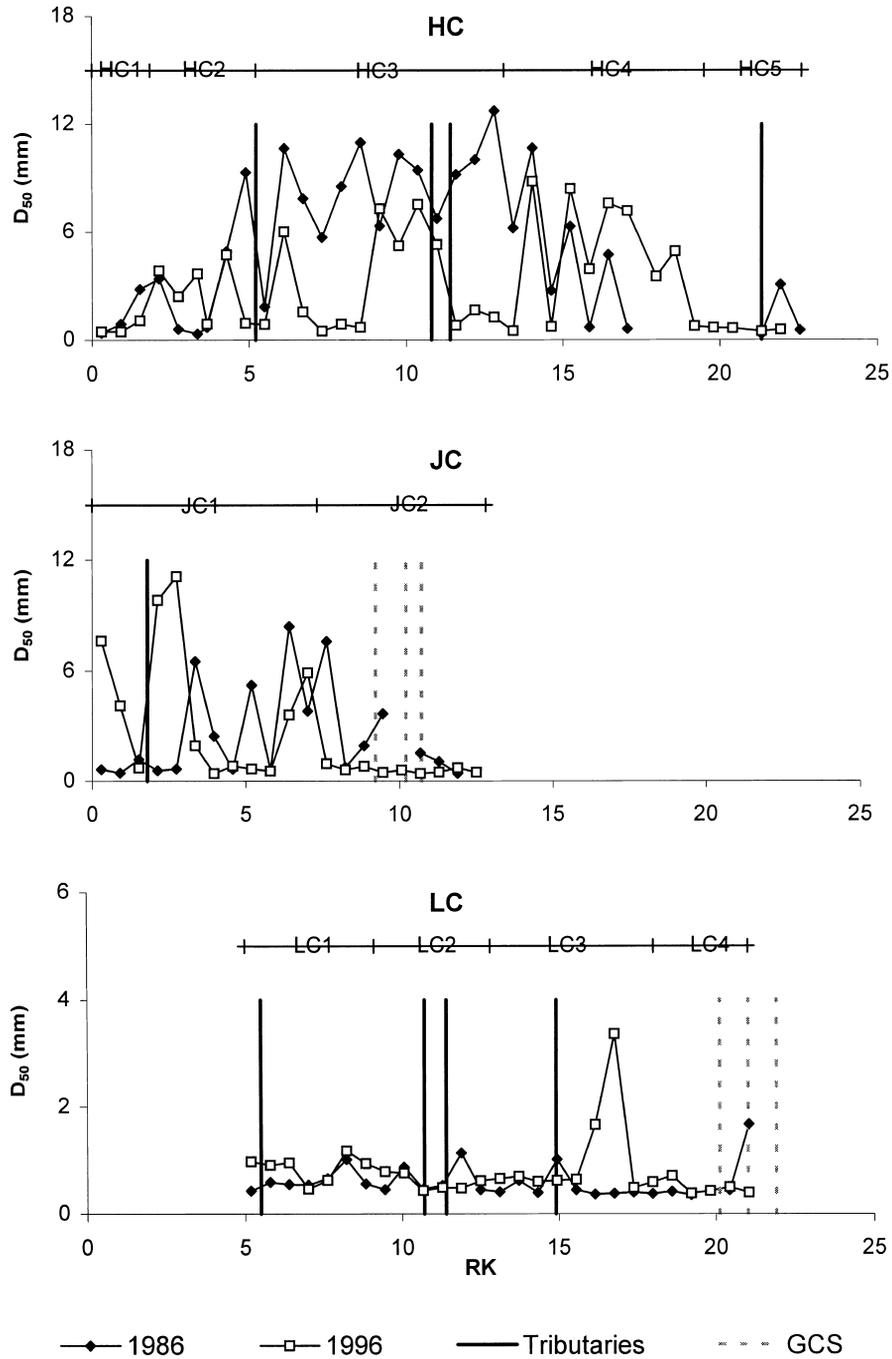


Fig. 5. Longitudinal profiles of D_{50} values for study channels in 1986 and 1996. Reaches and kilometers are assigned in the upstream direction.

Table 5

Spatial variation of mean D_{50} values for CEM reaches. Calculated differences are in respect to change from upstream to downstream

Year	Adjacent reaches		CEM stages		Mean D_{50} (mm)		Difference in D_{50} (mm)	Significant differences ^a	Predicted differences based on CEM stages
	Upstream	Downstream	Upstream	Downstream	Upstream	Downstream			
1986	HC2	HC1	V	VI	3.2	1.4	-1.8	None ($p = 0.15$)	HC2 > HC1
	HC3	HC2	IV	V	8.5	3.2	-5.3	HC3 > HC2 ($p < 0.01$)	HC3 > HC2 ^b
	HC4	HC3	III	IV	4.6	8.5	3.9	HC4 < HC3 ($p = 0.02$)	HC4 < HC3 ^b
	HC5	HC4	I	III	1.3	4.6	3.3	HC5 < HC4 ($p = 0.04$)	HC5 < HC4 ^b
	JC2	JC1	III	IV	2.6	2.5	-0.1	None ($p = 0.47$)	JC2 < JC1
	LC2	LC1	V	V	0.66	0.63	-0.03	None ($p = 0.42$)	None ^b
	LC3	LC2	IV	V	0.50	0.66	0.16	None ($p = 0.13$)	LC3 > LC2
	LC4	LC3	III	IV	0.72	0.50	-0.22	None ($p = 0.27$)	LC4 < LC3
1996	HC2	HC1	VI	VI	2.8	0.68	-2.1	HC2 > HC1 ($p = 0.01$)	None
	HC3	HC2	V	VI	3.0	2.8	-0.2	None ($p = 0.39$)	HC3 > HC2
	HC4	HC3	IV	V	5.3	3.0	-2.3	None ($p = 0.09$)	HC4 > HC3
	HC5	HC4	III	IV	1.7	5.3	3.6	HC5 < HC4 ($p = 0.02$)	HC5 < HC4 ^b
	JC2	JC1	IV	V	1.1	3.8	2.7	JC2 < JC1 ($p = 0.03$)	JC2 > JC1
	LC2	LC1	V	VI	0.60	0.87	0.27	LC2 < LC1 ($p = 0.02$)	LC2 > LC1
	LC3	LC2	IV	V	1.0	0.60	-0.4	None ($p = 0.10$)	LC3 > LC2
	LC4	LC3	IV	IV	0.49	1.0	0.51	None ($p = 0.06$)	None ^b

^aSignificance tested using F -test for variance and one-tailed T -test for mean.^bIndicates that observed direction of change was consistent with that predicted using CEM Stages.

texture were apparently due to a shift in the composition of the sediment mixture from sand to gravel, and not recruitment or retention of coarser particles (Table 4). For each channel, variation in the median size of the sand and gravel modes of the sediments explained less than 24% of the variation in overall D_{50} , but exponential functions of percent gravel explained 91%, 87%, and 69% of the variation in overall D_{50} for channels HC, JC, and LC, respectively (Fig. 4).

Examination of longitudinal profiles of median grain size (Fig. 5) shows that all three channels exhibited temporal and spatial variation. Profiles of grain size do not indicate downstream fining with the exception of the overall fining trend in reach HC3 (Fig. 5). This trend was not statistically significant, however, based on a runs test (Blalock, 1979). For the most part, longitudinal trends in grain size were not consistent in time (Fig. 5). For example, reach HC3 exhibited downstream fining in 1986 but was oscillatory in 1996. Although field notes indicated that tributaries were carrying loads coarser than the main channel, with few exceptions tributaries had no impact on the longitudinal grain size distributions (Fig. 5). Similarly, although grade control structures on LC and JC created backwater pools upstream and riffles downstream, they had no evident impact on bed texture.

The sampled reaches represented a range of evolutionary stages and sequences (Table 5). Spatial

variation of grain size was consistent with the modified CEM in 6 of 16 cases (Table 5). The 16 cases presented in Table 5 each have three possible outcomes, and the probability that a single prediction matches the corresponding observation by chance alone is $1/3 + 0.05 = 0.383$. Assuming that the 16 outcomes in Table 5 are independent, the probability of six or more correct predictions by chance alone is 0.620 (binomial theorem, $n = 16$, $r = 6$, Nelville and Dennedy, 1964). When the same logic is applied to the subset consisting of the eight HC reaches, the probability of the model predicting at least four of eight correctly (as was done using the modified CEM) by chance alone is 0.367.

All three channels exhibited temporal evidence of evolution toward higher stages during the period of observation (Table 5). HC represented the most complete sequence, ranging from Stages I to VI in 1986 (Stage II not present as HC was not channelized) and from III to VI in 1996. The other two study channels only represented portions of the complete sequence within any year when samples were taken (Table 5).

Only 4 of 11 reaches exhibited temporal changes in bed material size consistent with the modified CEM (Table 6), of which three were the prediction of no change. If we assume that the behavior of adjacent reaches is independent, the model could be expected to do at least this well by chance alone with a probability of 0.663 (binomial theorem, Nelville and Dennedy, 1964).

Table 6
Temporal variation of mean D_{50} values for CEM reaches

Reach	D_{50} (mm)		Change in D_{50} (mm)	CEM Stage		Significant changes in D_{50}^a	Predicted change based on CEM
	1986	1996		1986	1996		
HC1	1.4	0.68	-0.7	VI	VI	None ($p = 0.23$)	None ^b
HC2	3.2	2.8	-0.4	V	VI	None ($p = 0.38$)	Decrease
HC3	8.5	3.0	-5.5	IV	V	Decrease ($p < 0.01$)	Decrease ^b
HC4	4.6	5.3	0.7	III	IV	None ($p = 0.35$)	Increase
HC5	1.3	0.51	-0.8	I	III	None ($p = 0.28$)	Increase
JC1	2.5	3.8	1.3	IV	V	None ($p = 0.20$)	Decrease
JC2	2.6	1.3	-1.3	III	IV	None ($p = 0.12$)	Increase
LC1	0.63	0.87	0.24	V	VI	Increase ($p = 0.03$)	Decrease
LC2	0.66	0.60	-0.06	V	V	None ($p = 0.34$)	None ^b
LC3	0.50	1.0	0.5	IV	IV	None ($p = 0.06$)	None ^b
LC4	0.72	0.50	-0.22	III	IV	None ($p = 0.27$)	Increase

^aSignificance tested using F -test for variance and one-tailed t -test for mean.

^bIndicates that observed direction of change was consistent with that predicted using CEM Stages.

Clearly, the modified CEM did not provide reliable predictions concerning spatial or temporal bed material variations. However, when the changes observed for HC are examined without regard to the confidence levels for D_{50} differences, the model predicted the correct direction for all seven of the observed HC spatial changes (Table 5) and three of four temporal changes (Table 6).

6. Discussion

Studies of incised and disturbed channels have shown that the initial stages of channel recovery begin with the transfer of coarse sediment from upstream reaches to highly disturbed downstream reaches. This phenomenon has been observed in both spatial distribution patterns (Simon, 1989) and in changes of grain size through time (Simon and Thorne, 1996). If coarse material is not available, then changes in sediment discharge will be more drastic and persist for longer periods of time (Simon et al., 1996).

We attempted to develop and modify the conceptual model of incised channel evolution to include qualitative predictions of bed texture changes, and we tested this modified model using data collected over a 10-year period from three channels undergoing classical geomorphic evolution. Beds of these channels were composed of a bimodal mixture of sand and gravel so that the median grain size of the mixture was not well represented. However, the median sizes of the sands and gravels in these channels were relatively invariant, and D_{50} of the mixture was closely associated with the ratio of sand to gravel (Fig. 4). Evidently, changes in bed texture occurred primarily via changes in this ratio rather than through changes in particle sizes. Thus bed response to channel evolution was limited by the lack of coarse gravel supply. In addition, the largest particles we observed were frequently mobilized, thus limiting the magnitude of bed texture response via selective transport.

Because of the presence of coarse material in the bed and banks of JC and HC, and to a lesser degree LC (Fig. 3), we expected grain size to initially coarsen in response to channel incision. Only one sample reach represented pre-incision conditions: the

most upstream reach of HC (HC5) during 1986. This reach evolved from Stage I in 1986 to Stage III in 1996, but the attendant temporal change in grain size was insignificant. However, in 1986 the sediment within this reach (mean $D_{50} = 1.3$ mm) was significantly finer ($p < 0.01$, two-tailed t -test) than the material in all of the downstream reaches (mean $D_{50} = 5.7$ mm). The HC5 reach was located in the most upstream portion of the watershed (Fig. 2) where classical downstream fining schemes predict the coarsest bed. This case, the overall spatial distribution of mean grain sizes (Fig. 5), and the competence of the channels in relation to available sediment size, indicate that downstream fining is not a dominant process in these channels. Hence, alternative explanations for spatial and temporal distributions, such as the ones proposed using the CEM, merit examination.

Predictions of temporal changes in grain size along a channel are difficult, as evidenced by the inconsistency of the observations of others in incised and disturbed channels (Table 1). Lane's relation and some field studies (Willis, 1988; Bennett et al., 1998) suggest that beds will fine as a consequence of aggradation. However, other studies of incised and disturbed channels (Simon, 1989; Simon and Thorne, 1996) do not associate fining with aggradational response. Further, Jacobson (1995) noted that aggrading reaches of disturbed channels in southeastern Missouri coarsened in comparison with previous conditions. These conflicting findings suggest that general prediction of temporal changes in grain size in evolving channels will be difficult as different factors determine the outcome in different cases. For example, our modified CEM was accurate in only 4 of 11 cases of temporal prediction (Table 6), and three of these four were predictions of no change.

Modified CEM predictions for HC bed material were superior to predictions for the other two study streams, LC and JC. Because HC was never channelized and repositioned within its valley as the other two channels were, bed and bank sediment size may have been less variable as HC flowed down previous fluvial deposits allowing recruitment consistent with fluvial evolution. Selective transport of sediment contributions from eroding sources could also play a role in grain size variations. However, using conservative assumptions regarding critical shear stress, we

found all three of our study channels were more than competent to mobilize the largest bed material at flows less than bankfull. The relatively high sand content of the bed sediments implies that critical shear stresses were lower than we assumed (Wilcock, 1998), implying a relatively high frequency of bed mobilization. Indeed, along Goodwin Creek, an incising tributary to one of our channels, Kuhnle et al. (1989) showed that the coarsest bed sediment was mobilized, on average, 12.1 times per year. Clearly, the effect of differential mobility in these and similar incising channels is minimal. Channels with less sand should behave differently.

The effects contingent upon tributary and structure locations and the variation in sediment sources complicated the use of the modified CEM in the cases other than HC. The development of the modified CEM assumed that coarse material is stored in the bed and banks of the channels, or is available fluvially from upstream. The size of bank material, however, was highly variable along JC and LC because some eroding banks exposed gravel and others only finer materials (Fig. 3). Thus, the size and quantity of stored material, along with the location of sources within the watershed, play major roles in the development of longitudinal grain size distribution (Rice and Church, 1996). These factors are coupled with variables governing channel migration into sediment sources. CEMs allow prediction of sediment source locations, but whether these sources will yield coarse or fine material, and when they will be activated by channel erosion is a region-specific problem that must be solved through investigations of stratigraphic variability and the evolution of channel profile and planform.

7. Summary and conclusions

Conceptual models of incised channels link fluvial processes and forms in a framework that allows explanation of spatial and temporal trends. Existing CEMs do not include grain size, and existing grain size models are not appropriate for incised channels because of their exclusion of the sediment sources most important in incising systems. Existing CEMs offer a framework in which to predict relative changes in grain size. Assuming that a consistent supply of

coarse material is available in channel banks, bed, or fluvially from upstream, we suggest that bed material will coarsen in Stages III–V in comparison to the undisturbed state of the channel (Stage I), with the coarsest material occurring in Stage IV. Grain size in Stage IV, and to a lesser degree Stage V, is dominated by sediment supplied from bank failure. In this study area, banks contained extensive gravel deposits. It was also suggested that bed material will fine in Stages V and VI through continued bed aggradation and bank stabilization. The results of this study, however, did not support late-stage fining.

Grain size in incising channels can be just as dynamic as channel widths, depths, and slopes, with bed composition shifting from a mixture dominated by sand to one dominated by gravel, or vice versa, in a decade or less. This shift can be local or extend over reaches as long as 4 km. Changes in grain size are difficult to predict, and the use of a CEM provided limited results. Of the three study channels, the predicted directions of changes in grain size were consistent with those predicted using the qualitative model in only one of the channels. The successful case was an incising, meandering channel, which was in contrast to the other incising straightened channels used in the study. Longitudinal grain size distributions were governed by the size and quantity of material derived from lateral sediment sources (e.g. eroding banks), and the location of these sources within the watersheds. The influence of these sources has only recently received attention in grain size models, and deserves further attention in unstable watersheds.

Acknowledgements

This project was conducted while the first author was a graduate assistant for the Department of Civil and Environmental Engineering at the University of Mississippi. Funding for this project from the Water Quality and Ecology Unit of the USDA-ARS National Sedimentation Laboratory is greatly appreciated. We would like to thank Keith Parker for field assistance and providing historical photographs and channel descriptions and Nick Wallerstein for field assistance and discussions throughout this project. Paul Mitchell produced Figs. 1 and 2. Discussions

throughout this research with Steve Darby, Roger Kuhnle and Karin Boyd are appreciated. Reviews of an earlier version of this manuscript by James Pizuto, Stephen Rice and two anonymous reviewers are greatly appreciated.

References

- Barclay, J.S., 1980. Impact of stream alterations on riparian communities in Southcentral Oklahoma. FWS/OBS-80-17 (Fish and Wildlife Service Contract 14-16-0008-2039), Fish and Wildlife Service, Washington, DC.
- Barnard, R.S., 1977. Morphology and morphometry of a channelized stream: the case history of Big Pine Creek Ditch, Benton County, Indiana. *Studies in Fluvial Geomorphology* No. 4. Technical Report Number 92, Water Resources Research Center, Purdue University, West Lafayette, IN.
- Bennett, S.J., Simon, A., Kuhnle, R.A., 1998. Temporal variations in point bar morphology within two incised river meanders, Goodwin Creek, MS. *Proceedings of the International Conference on Water Resources Engineering*. American Society of Civil Engineers, New York, NY, pp. 1422–1427.
- Biedenham, D.S., Little, C.D., Thorne, C.R., 1990. Effects of low drop grade control structures on bed and bank stability. *Proceedings of the 1990 National Conference on Hydraulic Engineering*, San Diego, CA, 826–831.
- Blalock, H.M., 1979. *Social Statistics*. McGraw-Hill Kogakusha, Tokyo.
- Bluck, B.J., 1987. Bed forms and clast size changes in gravel-bed rivers. In: Richards, K.S. (Ed.), *River Channels: Environment and Process*. Basil Blackwell, Oxford, UK, pp. 159–178.
- Bray, D.I., 1982. Regime equations for gravel-bed rivers. In: Hey, R.D., Bathurst, J.C., Thorne, C.R. (Eds.), *Gravel-bed Rivers: Fluvial Processes, Engineering and Management*. Wiley, Chichester, UK, pp. 517–541.
- Chang, H.H., 1988. *Fluvial Processes in River Engineering*. Wiley, New York.
- Church, M., McLean, D., Wolcott, F.J., 1987. River bed gravels: sampling and analysis. In: Thorne, C.R., Bathurst, J.C., Hey, R.D. (Eds.), *Sediment Transport in Gravel Bed Rivers*. Wiley, Chichester, UK, pp. 43–79.
- Daniels, R.B., 1960. Entrenchment of the Willow Drainage Ditch, Harrison County, IA. *American Journal of Science* 258, 161–176.
- Darby, S.E., Thorne, C.R., 1996. Modelling the sensitivity of channel adjustments in destabilized sand-bed rivers. *Earth Surface Processes and Landforms* 21, 1109–1125.
- Doyle, M.W., 1997. Bed material size trends in incised channels. MS Thesis, University of Mississippi, Oxford, MS.
- Emerson, J.W., 1971. Channelization: a case study. *Science* 173, 325–326.
- Fenneman, N.M., 1938. *Physiography of the Eastern United States*. McGraw-Hill, New York, NY.
- Ferguson, R.T., Paola, C., 1997. Bias and precision of percentiles of bulk grain size distributions. *Earth Surface Processes and Landforms* 22, 1061–1077.
- Galay, V.J., 1983. Causes of river bed degradation. *Water Resources Research* 19, 1057–1090.
- Grissinger, E.H., Bowie, A.J., 1984. Material and site controls of stream bank vegetation. *Transactions of the ASCE* 27, 1829–1835.
- Grissinger, E.H., Murphey, J.B., 1983. Present channel stability and late Quaternary valley deposits in northern Mississippi. *International Association Sediment Special Publication* 6, 241–250.
- Grissinger, E.H., Murphey, J.B., 1984. Morphometric evolution of man-modified channels. In: Elliott, C.M. (Ed.), *River Meandering, Proceedings of the Conference Rivers '83*. American Society of Civil Engineers, New York, NY, pp. 273–283.
- Grissinger, E.H., Murphey, J.B., 1986. Bank and bed adjustments in a Yazoo Bluffline tributary. In: Wang, S.S.Y., Shen, H.W., Ding, L.Z. (Eds.), *Third International Symposium on River Sedimentation, Las Vegas, NV. River Sedimentation Vol. III* pp. 1003–1012.
- Grissinger, E.H., Murphey, J.B., Frederking, R.L., 1982. Geomorphology of upper Peters Creek Catchment, Panola County, Mississippi: Part 2. Within channel characteristics. *Proceedings of the International Symposium on Rainfall Runoff Modeling*. Water Resources Publications, Littleton, CO, pp. 267–282.
- Harvey, M.D., Watson, C.C., 1986. Fluvial processes and morphological thresholds in incised channel restoration. *Water Resources Bulletin* 22, 359–368.
- Hey, R.D., Thorne, C.R., 1986. Stable channels with mobile gravel beds. *Journal of Hydraulic Engineering* 112, 671–689.
- Hoey, T.B., Ferguson, R., 1994. Numerical simulation of downstream fining by selective transport in gravel bed rivers: Model development and illustration. *Water Resources Research* 30, 2251–2260.
- Hoey, T.B., Ferguson, R., 1997. Controls of strength and rate of downstream fining above a river base level. *Water Resources Research* 33, 2601–2608.
- Ichim, I., Radoane, M., 1990. Channel sediment variability along a river: a case study of the Siret River (Romania). *Earth Surface Processes and Landforms* 15, 211–225.
- Jacobson, R.B., 1995. Spatial controls on patterns of land-use induced stream disturbance at the drainage-basin scale — an example from gravel-bed streams of the Ozark Plateaus, MO. *Natural and Anthropogenic Influences in Fluvial Geomorphology*, *Geophysical Monograph* 89, 219–239.
- Julien, P.Y., Wargadalam, J., 1995. Alluvial channel geometry: theory and applications. *Journal of Hydraulic Engineering* 121, 312–325.
- Kesel, R.H., Yodis, E.G., 1992. Some effects of human modifications on sand-bed channels in southwestern Mississippi, USA. *Environmental Geology and Water Science* 20, 93–104.
- Knighton, A.D., 1980. Longitudinal changes in size and sorting of stream-bed material in four English rivers. *Geological Society of America Bulletin* 91, 55–62.
- Kodama, Y., 1992. Effect of abrasion on downstream gravel-size

- reduction in the Watarase River, Japan: field work and laboratory experiment. Paper 15, Environmental Research Center, Tsukuba, Japan.
- Kuhnle, R.A., 1996. Variations in bed material size on Goodwin Creek. Proceedings of the Sixth Federal Interagency Sedimentation Conference, Las Vegas, NV. pp. II-68–II-74.
- Kuhnle, R.A., Willis, J.C., 1992. Mean size distributions of bed load on Goodwin Creek. *Journal of Hydraulic Engineering* 118, 1443–1446.
- Kuhnle, R.A., Willis, J.C., Bowie, A.J., 1989. Variations in the transport of bed load sediment in a gravel-bed stream. Goodwin Creek, Northern Mississippi, U.S.A. Fourth International Symposium on River Sedimentation, Beijing, China.
- Lane, E.W., 1955. The importance of fluvial morphology in hydraulic engineering. *American Society of Civil Engineers Proceedings* 81, 1–17.
- Langedal, M., 1997. The influence of a large anthropogenic sediment source on the fluvial geomorphology of the Knabeana–Kvina rivers, Norway. *Geomorphology* 19, 117–132.
- Langendoen, E.J., Simon, A., Curini, A., Alonso, C.V., in press. Field Validation of an Improved Process-Based Model for Streambank Stability Analysis. Proceedings of the 1999 International Water Resources Engineering Conference. American Society of Civil Engineers.
- Lohnes, R.A., 1997. Stream degradation and stabilization: the Iowa experience. In: Wang, S.Y., Langendoen, E., Shields, F.D. Jr. (Eds.), *Management of Landscapes Disturbed by Channel Incision, Stabilization, Rehabilitation, and Restoration*, University of Mississippi, University, MS. pp. 35–44.
- Nelville, A.M., Dennedy, J.B., 1964. *Basic Statistical Methods for Engineers and Scientists*. International Textbook, New York.
- Nordin, C.F., Queene, B.S., 1992. Particle Size Distributions of bed sediments along the thalweg of the Mississippi River, Cairo, IL to head of passes. U.S. Army Corps of Engineers, Vicksburg District, Potamology Program (P-1) Report 7, Vicksburg, MS.
- Northwest Hydraulic Consultants, 1987. Black Creek Watershed Geomorphic Analyses for U.S. Army Corps of Engineers, Vicksburg District, Contract No. DACW38-87-D-0014, Vicksburg, MS.
- Northwest Hydraulic Consultants, 1989. Long Creek Watershed Field Investigation and Geomorphic Analyses for U.S. Army Corps of Engineers, Vicksburg District, Contract No. DACW38-88-D-0102, Vicksburg, MS.
- Novotny, V., Chesters, G., 1981. *Handbook of Nonpoint Pollution: Sources and Management*. Van Nostrand Reinhold, New York, NY.
- Nunnally, N.R., 1985. Application of fluvial relationships to planning and design of channel modifications. *Environmental Management* 9, 417–426.
- Parker, G., Andres, D., 1976. Detrimental effects of river channelization. Proceedings of the Symposium on Inland Waters for Navigation, Flood Control and Water Diversions, Fort Collins, CO. pp. 1248–1266.
- Parker, G., 1991a. Selective sorting and abrasion of river gravel: I. Theory. *Journal of Hydraulic Engineering* 117, 131–149.
- Parker, G., 1991b. Selective sorting and abrasion of river gravel: II. Applications. *Journal of Hydraulic Engineering* 117, 150–171.
- Pizzuto, J.E., 1995. Downstream fining in a network of gravel-bedded rivers. *Water Resources Research* 31, 753–759.
- Pizzuto, J.E., 1997. Combining geological and statistical methods with numerical modeling to evaluate the impacts of land use changes on rivers. In: Wang, S.S.Y., Langendoen, E.J., Shields, F.D. Jr. (Eds.), *Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision*. University of Mississippi Publishing, Oxford, MS, pp. 647–652.
- Rebich, R.A., 1993. Preliminary Summaries and Trend Analysis of Stream Discharge and Sediment Data for the Yazoo River Basin Demonstration Erosion Control Project, North-Central Mississippi, July 1985 Through September 1991. *Water-Resources Investigations Report 93-4068*, U.S. Geological Survey, Jackson, MS.
- Rice, S., Church, M., 1996. Bed material texture in low order streams on the Queen Charlotte Islands, British Columbia. *Earth Surface Processes and Landforms* 21, 1–18.
- Rinaldi, M., Simon, A., 1998. Bed-level adjustments in the Arno River, central Italy. *Geomorphology* 22, 57–71.
- Schoof, R.R., Allen, P.B., Gander, G.A., 1986. Evolution of two dredged channels in Oklahoma. Proceedings of the Fourth Federal Interagency Sedimentation Conference (FIASC), Washington, DC. pp. 5-93–5-102.
- Schumm, S.A., Harvey, M.D., Watson, C.C., 1984. *Incised Channels: Morphology, Dynamics, and Control*. Water Resources Publications, Littleton, CO.
- Seal, R., Paola, C., Parker, G., Southard, G.B., Wilcock, P.R., 1997. Experiments on downstream fining of gravel: I. Narrow-channel runs. *Journal of Hydraulic Engineering* 123, 874–884.
- Shields, F.D. Jr., Knight, S.S., Cooper, C.M., 1995. Rehabilitation of watersheds with incising channels. *Water Resources Bulletin* 31, 971–982.
- Shields, F.D. Jr., Milhous, R.T., 1992. Sediment and aquatic habitat in river systems. *Journal of Hydraulic Engineering* 118, 669–687.
- Simon, A., 1989. A model of channel response in disturbed alluvial channels. *Earth Surface Processes and Landforms* 14, 11–26.
- Simon, A., 1994. Gradation processes and channel evolution in modified West Tennessee streams: process, response and form. U.S. Geological Survey Professional Paper 1470, Washington, DC.
- Simon, A., Hupp, C.R., 1992. Geomorphic and vegetative recovery processes along modified stream channels of West Tennessee. U.S. Geological Survey Open-File Report 91-502, Nashville, TN.
- Simon, A., Darby, S.E., 1997. Disturbance, channel evolution and erosion rates: Hotophia Creek, MS. In: Wang, S.S.Y., Langendoen, E.J., Shields, F.D. Jr. (Eds.), *Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision*. University of Mississippi Publishing, Oxford, MS, pp. 476–481.
- Simon, A., Thorne, C.R., 1996. Channel adjustment of an unstable coarse-grained stream: opposing trends of boundary and criti-

- cal shear stress, and the applicability of extremal hypotheses. *Earth Surface Processes and Landforms* 21, 155–180.
- Simon, A., Rinaldi, M., Hadish, G., 1996. Channel evolution in the loess area of the Midwestern United States. *Proceedings of the Sixth Federal Interagency Sedimentation Conference, Interagency Advisory Committee on Water Data, Washington, DC*, III-86–III-93.
- Simons, D.B., Senturk, F., 1977. *Sediment Transport Technology*. Water Resources Publications, CO.
- Sternberg, H., 1875. Untersuchungen über Langen und Querprofil geschiebeführende Flüsse 25, 483–506, *Z. Bauwesen*.
- U.S. Army Corps of Engineers, 1990. Vicksburg district systems approach to watershed analysis for the Demonstration Erosion Control Project. Appendix A, Yazoo Basin, Mississippi, Demonstration Erosion Control Project, General Design Memorandum No. 54 (Reduced Scope), U.S. Army Engineer District, Vicksburg, MS.
- U.S. Army Corps of Engineers, 1993. Demonstration Erosion Control Project Monitoring Program Fiscal Year 1992 Report: Volume I: Main Text. Technical Report HL-93-3, U.S. Army Engineer District, Vicksburg, MS.
- Wang, L., Lyons, J., Kanehl, P., Gatti, R., 1997. Influences of watershed land use on habitat quality and biotic integrity in Wisconsin Streams. *Fisheries* 22, 6–12.
- Watson, C.C., Raphael, N.K., Biedenharn, D.S., 1997. Historical background of erosion problems in the Yazoo Basin. In: Wang, S.S.Y., Langendoen, E.J., Shields, F.D. Jr. (Eds.), *Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision*. University of Mississippi Publishing, Oxford, MS, pp. 115–119.
- Werritty, A., 1992. Downstream fining in a gravel-bed river in Southern Poland: lithologic controls and the role of abrasion. In: Billi, P., Hey, R.D., Thorne, C.R., Tacconi, P. (Eds.), *Dynamics of Gravel-bed Rivers*. Wiley, Chichester, UK, pp. 333–350.
- Whitten, C.B., Patrick, D.M., 1981. *Engineering Geology and Geomorphology of Streambank Erosion* (Report to Yazoo Basin Uplands, Mississippi). Technical Report GL-79-7, Report 2 of a Series, Vicksburg, MS.
- Wilcock, P.R., 1998. Two-fraction model of initial sediment motion in gravel-bed rivers. *Science* 280, 410–412.
- Willis, J.C., 1988. Partial armoring of sand beds by gravel. In: Mahmood, K., Haque, M.E., Coudri, A.M. (Eds.), *Mechanics of Alluvial Channels*. Water Resources Publications, Littleton, CO.
- Yearke, L.W., 1971. River erosion due to channel relocation. *Civil Engineering* 41, 39–40.